

A HARMONIC-SERIES FILTER

Technical Field of the Invention

The present invention relates in general to a series of filters to filter out a fundamental frequency and its harmonics.

Background of the Invention

Closed loop control systems are used in a wide variety of applications and generally provide good control. However, when sources of noise contaminate the control signals in closed loop systems, such closed loop control systems may fail to operate properly. The noise in a noise contaminated closed loop control systems often may be characterized by a slowly time-varying fundamental frequency component f_0 plus its harmonics. Such noise, for example, may be introduced into the control system by a nearby motor drive line.

Where noise contaminates the control signals of a closed loop control system to the point where the control system fails to operate properly, it is necessary to prevent or eliminate the noise. Generally, noise can be prevented from being introduced into the control system such as through the use of shielding, or noise can be removed from the control signals of the control system such as by the use of filtering. Shielding is often impractical, and filtering often introduces signal

impairments which can be as bad or worse than the noise.
As an example of the latter problem, noise removal by
lowpass filtering is often not acceptable because of the
amplitude and phase distortion introduced by the lowpass
filter and because of the destabilizing influence of the
resulting increased phase lag on the closed-loop system.

A low phase shift, low distortion noise
attenuation type of filter has the potential of providing
a better solution to the noise problem. Very narrow band
low distortion notch filtering for the removal of a
single spectral noise component are also well known.
Moreover, it is known to interconnect such notching
filters in order to remove plural offending noise
components. However, it has not been known how to tune
the notch filter sections so that the time-varying noise
components are effectively filtered. Moreover, known
narrow band notch filters are complex and do not combine
simplicity, low coefficient sensitivity, low roundoff
noise generation and propagation, and/or simple scaling
for a wide dynamic range.

The present invention, therefore, is directed
to a harmonic series filter which overcomes one or more
of the problems of the prior art.

Summary of the Invention

In accordance with one aspect of the present invention, a filtering system comprises first and second inputs, a set of M notch filters, a tuning parameter generator, a filter coefficient generator, and a gain normalizer. The first input receives a signal contaminated with noise. The second input receives a noise reference signal. Each of the M notch filters responds to a corresponding tuning coefficient by attenuating a corresponding noise frequency in the signal contaminated with noise. Based on the noise reference signal, the tuning parameter generator generates a tuning parameter corresponding to a fundamental frequency of the noise. The filter coefficient generator responds to the tuning parameter so as to provide each of the M notch filters with the corresponding tuning coefficient. The gain normalizer adjusts an overall gain of the M notch filters.

In accordance with another aspect of the present invention, a method comprises the following: generating a tuning parameter corresponding to a fundamental frequency of noise in a signal contaminated with the noise; generating tuning coefficients $\beta_1, \beta_2,$

β_3, \dots, β_N in response to the tuning parameter, wherein the tuning coefficients $\beta_1, \beta_2, \beta_3, \dots, \beta_N$ correspond to the fundamental frequency and to harmonics of the fundamental frequency; and, filtering the signal with
5 notches positioned at frequencies determined by the tuning coefficients $\beta_1, \beta_2, \beta_3, \dots, \beta_N$ so that the noise is attenuated.

In accordance with yet another aspect of the present invention, a notch filter comprises an input, an output, first, second, third, fourth, and fifth summers, first and second multipliers, and first and second delays. The input receives an input signal contaminated with noise, and the noise has a fundamental frequency. The output provides an output signal from the notch
10 filter, and the output signal is substantially free of a harmonic of the fundamental frequency of the noise. The first summer sums the input signal with an output of the first delay, and the first summer has an output providing the output signal. The first multiplier multiplies the
15 output signal by a gain coefficient. The second summer subtracts an output of the first multiplier from the input signal. The third summer subtracts an output of a second delay from an output of the second summer. The
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second multiplier multiplies an output of the third summer by a tuning coefficient related to the harmonic. The fourth summer subtracts an output of the second multiplier from the output of the second summer, and the fourth summer has an output coupled as an input to the second delay. The fifth summer subtracts the output of the second multiplier from the output of the second delay, and an output of the fifth summer is coupled as an input to the first delay.

In accordance with still another aspect of the present invention, a notch filter applies a transfer function $F(z,n)$ to an input signal contaminated with noise in order to produce an output signal in which a harmonic of the noise is attenuated. The transfer function $F(z,n)$ is defined by the following equation:

$$F(z,n) = \frac{1 - 2\beta_n z^{-1} + z^{-2}}{1 - \beta_n(1 + \alpha)z^{-1} + \alpha z^{-2}}$$

where n designates the harmonic, β_n is a tuning coefficient related to a center frequency of a bandwidth of the notch filter, α is a quantity related to the bandwidth of the notch filter, z^{-1} represents a first order delay, and z^{-2} represents a second order delay.

Brief Description of the Drawings

These and other features and advantages will become more apparent from a detailed consideration of the invention when taken in conjunction with the drawings in which:

Figure 1 shows an overview of a filtering system according to one embodiment of the present invention;

Figure 2 shows in additional detail a representative one of the notch filters of the filtering system shown in Figure 1; and,

Figure 3 shows in additional detail the filter coefficient computer of Figure 2.

Detailed Description

Figure 1 shows a filtering system 10 for filtering out the fundamental and harmonic frequency components of noise introduced into a signal by a source of noise, such as a nearby motor drive line. The filtering system 10, for example, may be digital filtering system whose sampling period is T. The filtering system 10 includes a tuning parameter extractor 12 which receives a noise reference signal on an input

14. This noise reference signal may be provided, for example, by a monitor positioned to pick up the noise emanating from the noise source of concern. One of the advantages of using a noise reference signal is that the filtering system 10 can then follow any changes in phase or frequency of the noise. Thus, the filtering system 10 adapts to the noise environment.

The tuning parameter extractor 12 may be a phase-locked loop or a frequency-locked loop that derives the fundamental frequency f_0 of the noise reference signal and then provides a tuning parameter β_1 on an output 16 based upon the fundamental frequency f_0 in accordance with the following equation:

$$\beta_1 = \cos(2\pi f_0 T) \quad (1)$$

where T is the sampling period.

The output 16 of the tuning parameter extractor 12 is coupled to an input of a filter coefficient computer 18 which provides, on a tuning coefficient bus 20, a set of filter tuning coefficient β_n for $n = 1, 2, 3, \dots, N$ in accordance with the following equation:

$$\beta_n = \cos(2\pi f_0 n T) \quad (2)$$

where N is the number of possible harmonics.

Depending on the noise source, one or more of the N harmonics of the noise fundamental frequency may not be present in the noise signal. If such a source is the noise source of concern, it is necessary to use only the tuning coefficients corresponding to the M harmonics that are present, such that the tuning coefficients corresponding to the others of the N possible harmonics that are not present may be ignored. The fundamental frequency of the noise is f_0 and the frequencies of the N harmonics of the noise fundamental frequency are $f_n = nf_0$ where $n = 1, 2, \dots, N$. The notch-filter tuning coefficients for attenuating these interfering frequency components are defined in accordance with the following equation:

$$\beta_n = \cos(2\pi f_n T) \quad (3)$$

If some harmonics are absent, only $M < N$ frequency components (f_m where $m = 1, 2, \dots, M$) are present, and the required notch-filter tuning coefficients are given by the following equation:

$$\beta_m = \cos(2\pi f_m T) \quad (4)$$

However, as will be understood from the above, although each f_m is an integer multiple of f_0 , generally $f_m \neq mf_0$. Although the filter coefficient computer 18 generates all N values of β , only the M required values are output onto the tuning coefficient bus 20. Therefore, the filter coefficient computer 18 contains instructions that determine which output samples $\beta_1, \beta_2, \beta_3, \dots, \beta_N$ are to be provided on the tuning coefficient bus 20. These instructions are based on the frequencies known to be in the noise signal.

The noise contaminated input signal is received on an input 22. A gain normalizer 24 attenuates the noise contaminated input signal in accordance with the following equation:

$$\left[\frac{(1 + \alpha)}{2} \right]^M \quad (5)$$

The quantity α in equation (5) is given by the following equation:

$$\alpha = \frac{1 - \tan(\pi f_{BW} T)}{1 + \tan(\pi f_{BW} T)} \quad (6)$$

where α is the common bandwidth parameter for each filter stage. The common -3 dB bandwidth (in Hz) of each notch filter is the desired bandwidth f_{BW} . The gain normalizer 24 provides the attenuated noise contaminated input signal on an output 26 which is coupled to a filter bank 28 comprising the M required notch filters $30_1, 30_2, 30_3, \dots, 30_M$ coupled in tandem. An output 32 from the last notch filter 30_M is a substantially noise free version of the signal on the input 22 with little phase and amplitude distortion.

A notch filter 50 is shown in Figure 2 and may be used for each of the notch filters $30_1, 30_2, 30_3, \dots, 30_M$ shown in Figure 1. Each of the notch filters $30_1, 30_2, 30_3, \dots, 30_M$ is a second-order single-multiplier-per-order Gray-Markel lattice all-pass filter based upon the filters shown by A. H. Gray, Jr. and J. D. Markel in "Digital lattice and ladder filter synthesis," IEEE Trans. on Audio and Electroacoustics, vol. AU-21, Dec. 1973; pp. 491-500, although the notch filter 50 could be based on any of the other n-multiplier per order filters described therein. P. A. Regalia, S. K. Mitra, and P. P. Vaidyanathan, in "The digital allpass filter; a versatile building block," Proc. IEEE, vol. 76, January, 1988; pp.

19-37, have shown that all pass filters may be interconnected in interesting ways to produce standard filtering functions with reduced complexity and high precision. Furthermore, U.S. Patent No. 5,587,910 has shown a sign-assignment protocol that gives maximum dynamic range to a Gray-Markel lattice filter section.

The transfer function of the notch filter 50 shown in Figure 2 is given by the following equation:

$$F(z,n) = \frac{1 - 2\beta_n z^{-1} + z^{-2}}{1 - \beta_n(1 + \alpha)z^{-1} + \alpha z^{-2}} \quad (7)$$

where β_n is the tuning coefficient supplied to the notch filter 50 and α is given by equation (6). The notch filter 50 implements this transfer function in a simple manner and with a large dynamic range. The zero frequency gain for the transfer function of equation (7) is given by the following:

$$\frac{2}{1 + \alpha} \geq 1 \quad (8)$$

where the -3 dB notch-width parameter α is common to all of the filter sections and is given by equation (6) and where the -3 dB notch width in Hz is f_{BW} .

5 The input signal on an input 52 of the notch filter 50 is coupled to a first positive input of a first summer 54. The output of the first summer 54 delivers the output of the notch filter 50 on an output 56 and is also coupled to a bandwidth scaling multiplier 58 that applies the quantity α to the output of the first summer 54. The bandwidth scaling multiplier 58 sets a -3 dB notch bandwidth on the notch implemented by the notch filter 50 in accordance with α . The output of the bandwidth scaling multiplier 58 is coupled to a negative input of a second summer 60. The input signal on the input 52 of the notch filter 50 is also coupled to a positive input of the second summer 60.

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15 The output of the second summer 60 is coupled to a positive input of a third summer 62 and to a positive input of a fourth summer 64. The output of the third summer 62 is coupled to a tuning coefficient multiplier 66 which forms the product of the output of third summer 62 and the tuning coefficient β_n from the tuning coefficient bus 20. The output of tuning

coefficient multiplier 66 is coupled to a negative input of the fourth summer 64 and to a negative input of a fifth summer 68. The output of fourth summer 64 is coupled as an input of a first single-sample-period-delay element 70 whose output is connected to a negative input of the third summer 62 and to a positive input of the fifth summer 68. The output of the fifth summer 68 is coupled to a second single-sample-period-delay element 72 whose output is coupled to a second positive input of the first summer 54.

The notch filter 50 shown in Figure 2 is a narrow band notch filter that is centered on the n^{th} harmonic of the fundamental noise frequency as determined by the tuning coefficient β_n . Thus, each of the notch filters $30_1, 30_2, 30_3, \dots, 30_M$ filters out a corresponding fundamental or harmonic frequency of the noise signal at the input 22 to produce a substantially noise free signal at the output 32.

The filter coefficient computer 18 as shown in Figure 3 is implemented as a second order recursive loop. The fundamental frequency tuning parameter β_1 provided by the tuning parameter extractor 12 is supplied as the initial condition to a first single-sample-period delay

element 82 and also to a first input of a multiplier 84. An output Γ_n from the first single-sample-period delay element 82 is coupled to a negative input of a summer 86. The output of the summer 86 is coupled as an input to a
5 second single-sample-period delay element 88 whose initial condition is set to unity. The output of the second single-sample-period delay element 88 is coupled to a second input of the multiplier 84 and to the Γ_{n+1} input of the first single-sample-period delay element 82. Also, the output of the second single-sample-period delay element 88 provides the tuning coefficients $\beta_1, \beta_2, \beta_3, \dots, \beta_N$ over the tuning coefficient bus 20. The output of the multiplier 84 is coupled through a multiply-by-two device 90 to a positive output of the summer 86. Accordingly, the filter coefficient computer 18
10 recursively generates the tuning parameters $\beta_1, \beta_2, \beta_3, \dots, \beta_N$ and provides these tuning parameters over the tuning coefficient bus 20.

20 Certain modifications of the present invention will occur to those practicing in the art of the present invention. For example, the present invention has been described above in terms of eliminating noise from such noise sources as a motor drive line. However, it should

be understood from the above description that the filter of the present invention may be used to filter out noise from other sources as well.

Moreover, the embodiment of the present invention described above includes certain hardware components as shown in Figures 1-3. The present invention can be implemented, however, using a computer, a digital signal processor, a neural network, one or logic arrays, etc.

As described above, the tuning parameter extractor 12 extracts a tuning parameter β_1 , and the filter coefficient computer 18 is a second order recursive loop which recursively generates the tuning coefficients $\beta_1, \beta_2, \beta_3, \dots, \beta_N$ using the tuning parameter β_1 as an input. Instead, the tuning parameter extractor 12 may be arranged to simply extract the noise fundamental frequency f_0 as the tuning parameter, and the filter coefficient computer 18 may be arranged to implement equation (2) directly in order to generate the tuning coefficients $\beta_1, \beta_2, \beta_3, \dots, \beta_N$ from upon the tuning parameter f_0 .

Furthermore, as described above, the filter bank 28 is shown as including the notch filters 30₁, 30₂,

30₃, . . . 30_M. Thus, a determination is made beforehand as to which noise frequencies will be present and which ones will not be present in the noise generated by the noise source. The tuning coefficient bus 20 is then arranged to deliver only the tuning coefficients generated by the filter coefficient computer 18 that correspond to the noise frequencies which are predicted to be present. These noise frequencies may change as the noise fundamental frequency changes. However, any changes in the noise fundamental frequency are tracked and are used to suitably adjust the tuning coefficients.

On the other hand, if it cannot be predicted which noise frequencies will be in the noise generated by the noise source, a harmonic analyzer can be used to determine which harmonics are present in the noise reference signal on the input 14. In this case, the filter bank 28 should contain the notch filters 30₁, 30₂, 30₃, . . . 30_N where N represents the maximum number of noise frequencies likely to be encountered in the noise reference signal received over the input 14. The output of the harmonic analyzer can then be used to control the tuning coefficient bus 20 to deliver to the required number of notch filters the tuning coefficients

corresponding to the actual noise frequencies and to by-pass the unneeded notch filters, if any.

Accordingly, the description of the present invention is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the best mode of carrying out the invention. The details may be varied substantially without departing from the spirit of the invention, and the exclusive use of all modifications which are within the scope of the appended claims is reserved.